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LETTER

Impact of Indo-Pacific warm pool Hadley circulation on the seasonal forecast performance for summer precipitation over the western North Pacific

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Abstract

The western North Pacific summer climate affects the densely populated East Asian countries, while seasonal forecasting over these regions remains challenging for dynamical models. This study evaluates the effect of the spring Indo-Pacific warm pool (IPWP) Hadley circulation on the forecast performance for summer western North Pacific (WNP) precipitation in the Met Office Global Seasonal Forecast System (GloSea5). GloSea5 skillfully predicts IPWP Hadley circulation, but has moderate forecast skill for summer WNP precipitation. Compared to observations, the significant relationship between the spring IPWP Hadley circulation and the summer WNP precipitation is overestimated in most hindcast members and in the ensemble mean. Furthermore, we confirmed that the forecast ensemble members with a stronger such regional circulation–precipitation relationship have better forecast performance for the summer WNP precipitation, suggesting the importance of such a relationship for the seasonal forecast of WNP precipitation. These results also imply the need to further investigate other important factors for the WNP precipitation, the effects of which may be suppressed by the overestimated regional circulation–precipitation relationship in GloSea5.

1. Introduction

The western North Pacific (WNP) witnesses frequent tropical cyclone activity and heavy rainfall in summer, which causes severe disasters in densely populated coastal regions (e.g. Mendelsohn *et al* 2012, Peduzzi *et al* 2012, Feng and Tsimplis 2014, Guo and Tan 2018a, 2018b). Thus, it is important to develop skillful seasonal forecasts for WNP summer climate. Efforts have been made to advance the seasonal forecast skill of dynamical models over the WNP (e.g. Lee *et al* 2011, Kosaka *et al* 2013, Wang *et al* 2013, Li *et al* 2014). Several precursor signals in winter and spring, such as the El Niño–Southern Oscillation (ENSO), the Arctic Oscillation, and the regional Hadley circulation over the Indo-Pacific warm pool (IPWP), significantly correlate with the WNP summer climate (e.g. Wang *et al* 2000, Gong *et al* 2011, Guo and Tan 2018b). These precursor signals have been used as important predictors in a variety of statistical seasonal forecast models (e.g. Chan et al 1998 , Chan *et al* 2001, Camargo and Barnston 2009). Although including these predictors has improved statistical forecast performance, the WNP summer climate forecasts remain challenging due to prediction barriers, such as ENSO evolution (e.g. Latif *et al* 1998, Turner *et al* 2005) and the nonlinear behavior of the climate system across temporal scales (e.g. Palmer 2006). The spring IPWP Hadley circulation may be closely connected to the summer WNP climate, especially for precipitation and tropical cyclone activity (e.g. Zhou and Cui 2008, Guo and Tan 2018b). The spring IPWP Hadley circulation signal can persist to the following summer and modulate large-scale environmental factors, which significantly affect summertime WNP climate (Guo and Tan 2018b). Using an air–sea coupled model, Kosaka *et al* (2013) suggested that WNP summer climate is dynamically connected to the spring cross-equatorial wind over the IPWP. These results suggest the potential to diagnose the persisting effect of spring IPWP Hadley circulation on the summer WNP climate in dynamical models. Thus, the question arises as to whether dynamical seasonal forecast models can capture the cross-seasonal relationship between spring IPWP Hadley circulation and summer WNP precipitation and, if so, how this relationship affects the forecast performance of the dynamical model.

Among the state-of-the-art seasonal forecast models, the Met Office Global Seasonal Forecast System version 5 (GloSea5) shows good seasonal forecast skill for the Indian summer monsoon (e.g. Johnson *et al* 2017, Chevuturi *et al* 2019) and the South China Sea monsoon (Martin *et al* 2019). In contrast, it has less skill at predicting summer rainfall over most regions of the WNP (Johnson *et al* 2017) and tropical cyclone activity (e.g. Camp *et al* 2015, 2019, Feng *et al* 2020). This variability of forecast skills with spatial and temporal scale suggests that seasonal predictability for these phenomena in GloSea5 arises from different prediction sources or that some spatial and temporal scales may be inherently more predictable than others. In the present study, we investigate the seasonal prediction performance of summer WNP precipitation in GloSea5, by focusing on whether this seasonal prediction performance varies with the initial states of the large-scale circulations or the impacts of regional circulation–precipitation relationships.

2. Datasets and methodology

In this study, 23 years of seasonal ensemble hindcast simulations (1993–2015) were employed from the Global Coupled 2.0 configuration of GloSea5 (GloSea5-GC2; MacLachlan *et al* 2015) at N216 resolution (approximately 0.833° × 0.556° in longitude and latitude) with 85 vertical levels. For each year, we use four hindcast start dates: 1, 9, 17, and 25 February. There are seven ensemble members for each start date; each member is a seven-month forecast. Thus, we have 28 hindcast members in total for each year, which yield 28 time series of summer WNP precipitation forecasts for 1993–2015. Because these 28 forecast members are independent, their sequence can be reorganized randomly (e.g. Johnson *et al* 2017). We randomly reorganized these 28 ensemble members 5000 times, generating 28 × 5000 random samples that can be used to explore the relationship between IPWP Hadley circulation and summer WNP precipitation as well as their influence on forecast performance. Increasing the number of random samples does not qualitatively change the results. We define March–May as spring and June–August as summer. It is worth noting that the last initial date (25 February) lags the first one (1 February) by nearly one month. The effect of forecast leading times on the forecast skills will be examined in the result sections.

We analyze GloSea5 forecasts of precipitation, sea level pressure (SLP) and horizontal winds on pressure levels. For validation, we use precipitation from the Global Precipitation Climatology Project (GPCP, Adler *et al* 2003), and SLP and horizontal winds from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim) dataset (Dee *et al* 2011), during the same period.

We compute the vertical shear of the zonal mean divergent components of the meridional winds between 200 hPa and 850 hPa, similar to previous studies, to represent the cross-equatorial component of the regional Hadley circulation (e.g. Ambrizzi *et al* 2005, Wang 2005, Mantsis and Clement 2009, Chen *et al* 2014). We use the correlation coefficients of inter-annual anomalies between GloSea5 and GPCP (or ERA-Interim) during 1993–2015 to denote the seasonal forecast performance (or prediction skill). The statistical significance of the regression and correlation analysis was tested by using a two-tailed Student's *t*-test. We also employed the Kolmogorov–Smirnov (K–S) test to check whether the difference between the probability density distributions of two samples is statistically significant.

3. Results

3.1. Seasonal forecast performance of WNP precipitation

The climatological mean biases and forecast skill for summer WNP precipitation in GloSea5 beginning in February are shown in figure 1, based on the ensemble mean of the 28 members. There are obvious wet biases over the WNP (figure 1(a)), which is consistent with previous studies using MetUM climate simulations (e.g. Bush *et al* 2015, Peatman and Klingaman 2018). These biases are located over the latitude band of 0°–20°N, with the maximum centered over the WNP (figure 1(a)). In contrast to the mean biases, GloSea5 has higher forecast performance over the simulated monsoon trough region than the surrounding areas (figure 1(b)). This also indicates the independence of forecast skill to the mean bias for summer WNP precipitation. Because the precipitation and circulation over the WNP area (5°N–25°N, 125°E–180°) influences the East Asian climate (e.g. Kosaka *et al* 2013, Zhang *et al* 2016), we target this region for further analysis. Slightly perturbing the boundary of this region does not alter the conclusions. Figure 1(c) shows the probability distribution function (PDF) of forecast performance for summer WNP precipitation based on the 28 × 5000 reorganized samples. The most probable correlation coefficient is approximately 0.55, which is slightly lower than the correlation for the ensemble mean of the original 28 members ($r = 0.69$). As the hindcasts start on different initial dates in February, the slight differences in lead time may affect the prediction skill of summer WNP precipitation. We tested this by resampling each of the original seven-member ensembles (initialized on 1, 9, 17, and 25 February) 5000 times to form four groups of 7 × 5000 reorganized samples. Analysis of these samples shows that the initialization date has little effect on forecast performance of summer WNP precipitation (supplementary figure 1)(available online at stacks.iop.org/ERL/15/104041/mmedia). The most probable correlation coefficients are nearly identical for the initializations on 1, 9, and 25 February, except for a little difference in their kurtosis and skewness. The initialization on 17 February has a slightly lower most probable correlation coefficient (approximately 0.43).

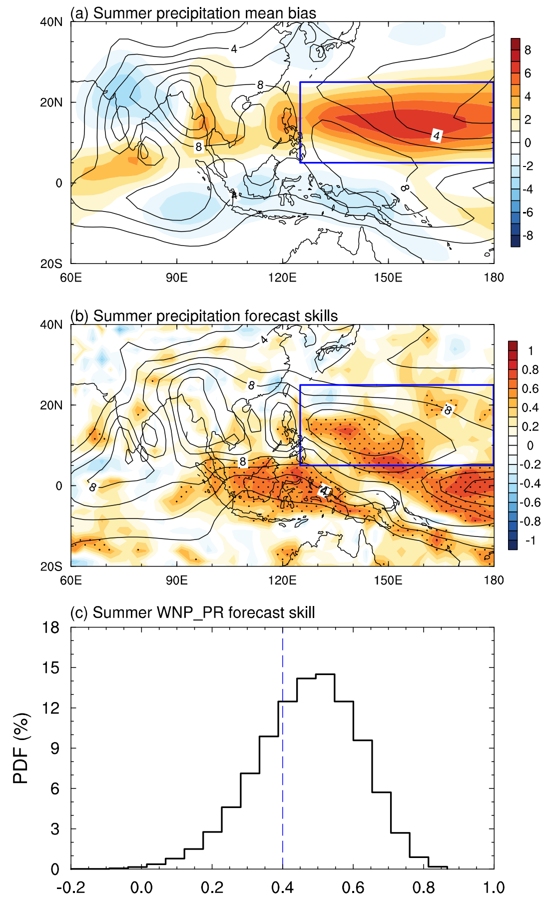

Figure 1. (a) Climatological mean summer precipitation based on GPCP (contour, mm day^{-1}) and its difference against GloSea5 hindcast ensemble mean (shading, mm day^{-1}, GloSea5 minus GPCP). (b) Forecast skill of summer precipitation in GloSea5 (shading) and climatological mean summer precipitation from GloSea5 hindcasts ensemble mean (contour, mm day^{-1}). Blue boxes indicate the target area (5°N–25°N, 125°E–180°) for the WNP precipitation. (c) PDF of the forecast skill for the areal mean summer precipitation over the WNP. The stippled area in (b) indicates where forecast skill is significant at the 95% confidence level. The blue dashed line in (c) indicates the 95% confidence level.

3.2. Cross-seasonal relationship between spring IPWP Hadley circulation and summer WNP precipitation

Figures 2(a) and (c) show spring circulation anomalies regressed on summer WNP precipitation in GloSea5 and reanalysis. In the lower troposphere (850 hPa), the positive summer WNP precipitation anomaly corresponds to a strong cyclonic circulation and negative SLP anomalies over the WNP, with a northward cross-equatorial wind over the IPWP. In the upper troposphere (200 hPa), there is strong divergence over the WNP with southward divergent wind anomalies crossing the equator (figures 3(a) and (c)). The circulation patterns at upper and lower troposphere indicate an obvious cross-equatorial overturning circulation over the IPWP. GloSea5 shows coherent circulation patterns with the reanalysis, indicating a well-represented relationship between the summer WNP precipitation and spring IPWP Hadley circulation in GloSea5. In addition, the forecast skill for spring IPWP Hadley circulation is much higher than that for summer WNP precipitation, with the correlation coefficient $r = 0.83$ for ensemble mean and with the most probable correlation coefficients near 0.78.

We further defined an index as the averaged vertical shear of the divergent meridional winds over 10°S–10°N, 80°E–180° to represent IPWP Hadley circulation (Guo and Tan 2018b). Figures 2(b) and (d) show summer circulation and precipitation regressed on the spring IPWP Hadley circulation, based on both GloSea5 and reanalysis. Strong positive spring IPWP Hadley circulation anomalies correspond to positive precipitation anomalies over the WNP and enhanced cyclonic circulation anomalies at 850 hPa. At the upper levels, there are strong divergent winds over the WNP and convergent winds returning to the Southern Hemisphere (figures 3(b) and (d)). This cross-seasonal relationship is captured in GloSea5. It is interesting to see that the anomalous precipitation patterns related to spring IPWP Hadley circulation (figures 3(b) and (d)) resemble the Pacific–Japan teleconnection pattern (e.g. Kosaka *et al* 2013). The Pacific–Japan pattern is largely forced by the tropical Pacific sea surface temperature anomaly (SSTA) in winter (e.g. Kosaka *et al* 2013). Chakraborty (2018) also suggested that the preceding winter Niño-3.4 index is closely related to the atmospheric circulations and precipitation over the IPWP region in summer. These results indicate that spring

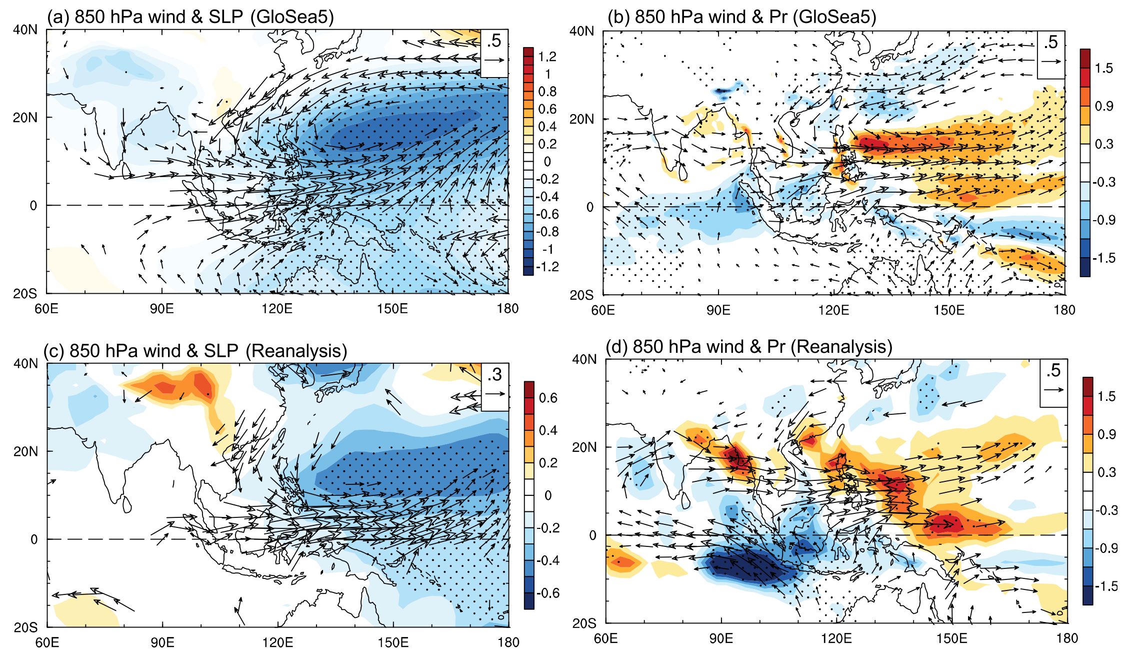

Figure 2. (a) Spring 850 hPa horizontal wind (vectors, m s^{-1}) and SLP (shading, hPa) regressed on standardized summer WNP_PR over the region 5°N–25°N, 125°E–180° in GloSea5. (b) Anomalies of summer 850 hPa horizontal wind (vectors, m s^{-1}) and precipitation (shading, mm day^{-1}) regressed on standardized IPWP_HC over the region 10°S–10°N, 80°E–180° in the GloSea5 forecast. (c, d) As in (a, b), but for reanalysis. The stippled area indicates statistically significant values at the 95% confidence level. The vectors only show the wind regressions significant at the 95% confidence level.

IPWP Hadley circulation acts as an intermediate link between winter tropical Pacific SSTA and summer WNP precipitation (e.g. Guo and Tan 2018b).

3.3. Effect of spring IPWP Hadley circulation on summer WNP precipitation seasonal prediction

To further evaluate the correlation coefficient between spring IPWP Hadley circulation and summer WNP precipitation (indicated by $r_{(\mathrm{HC, PR})}$ hereafter), figure 4(a) shows the PDF of $r_{(\mathrm{HC, PR})}$ based on the 28 × 5000 reorganized ensembles. The most probable $r_{(\mathrm{HC, PR})}$ in GloSea5 is near 0.55, which is larger than that in reanalysis ($r = 0.45$), but the values of $r_{(\mathrm{HC, PR})}$ have a wide range of –0.2∼0.9. About 27% of $r_{(\mathrm{HC, PR})}$ samples are statistically insignificant. Given the close relationship between spring IPWP Hadley circulation and summer WNP precipitation, we further use this distribution to classify these 28 × 5000 members into groups and analyze whether the prediction performance for summer WNP precipitation depends on that of spring IPWP Hadley circulation, or whether the relationship between spring IPWP Hadley circulation and summer WNP precipitation influences the skill at summer WNP precipitation prediction.

Figure 4(b) shows the PDF of summer WNP precipitation forecast performance based on samples with spring IPWP Hadley circulation forecast skill larger or smaller than the mean value (0.78) of the 28 × 5000 samples. There is no statistically significant difference in summer WNP precipitation forecast skill between the two sample groups according to the K–S test, which means that spring IPWP Hadley circulation forecast skill has little influence on forecast skill for summer WNP precipitation. Next, we test whether representability of their cross-seasonal relationship influences summer WNP precipitation forecast skills.

Recall that in GloSea5, 73% of the reorganized samples can reproduce a statistically significant $r_{(\mathrm{HC, PR})}$, with the most probable $r_{(\mathrm{HC, PR})}$ near 0.55, which is larger than $r_{(\mathrm{HC, PR})} = 0.45$ in the reanalysis. To investigate the possible influence of $r_{(\mathrm{HC, PR})}$ on the summer WNP precipitation skill, the samples are also divided into two groups: one for significant $r_{(\mathrm{HC, PR})}$ ($p < 0.05$), and the other for insignificant $r_{(\mathrm{HC, PR})}$ ($p > 0.05$). Figure 4(c) shows the PDF of the forecast skill for summer WNP precipitation in these two groups. The PDF of forecast samples with significant $r_{(\mathrm{HC, PR})}$ shows an obvious shift towards larger forecast skill compared to those samples with insignificant $r_{(\mathrm{HC, PR})}$. The PDF difference between significant and insignificant $r_{(\mathrm{HC, PR})}$ samples is statistically significant in the K–S test ($p < 0.01$). Thus, the samples with strong $r_{(\mathrm{HC, PR})}$ have higher skill for summer WNP precipitation than those with weak $r_{(\mathrm{HC, PR})}$. To investigate whether the slight difference in lead time among the four initialization dates (1, 9, 17, and 25 February) affects the results in figure 4(c), we further show the PDFs of performance for the four dates

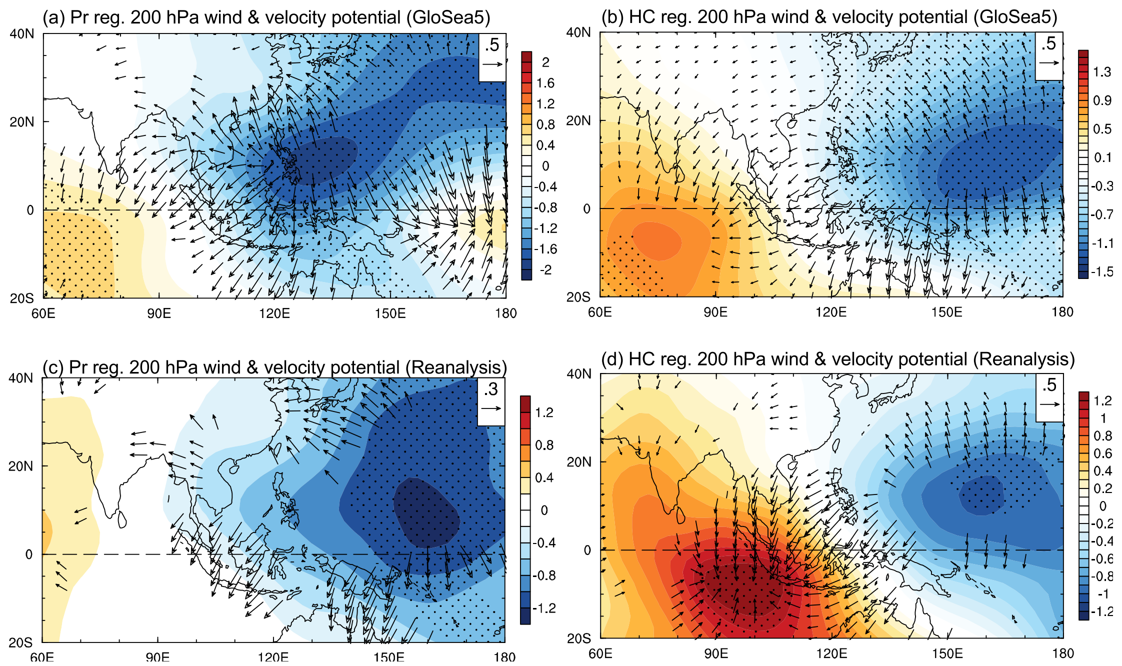

Figure 3. (a) Spring 200 hPa divergent wind (vectors, m s^{-1}) and velocity potential (shading, 10^6 m^2 s^{-1}) anomalies regressed on standardized summer WNP precipitation over the region 5°N–25°N, 125°E–180° in GloSea5. (b) Summer 200 hPa divergent wind (vectors, m s^{-1}) and velocity potential (shading, 10^6 m^2 s^{-1}) anomalies regressed on standardized IPWP Hadley circulation over the region 10°S–10°N, 80°E–180° in the GloSea5 forecast. (c, d) As in (a, b), but for reanalysis. The stippled area indicates statistically significant values at the 95% confidence level. The vectors only show the wind regressions significant at the 95% confidence level.

separately (supplementary figure 2), using the 5000 resampled ensembles constructed earlier. Each of the four initializations shows consistently improved performance for the significant $r_{(HC,\,PR)}$ samples (supplementary figure 2), as shown in figure 4. The slight difference in these initialized forecasts might be related to the limited sample size (e.g. seven members). These results indicate that increasing $r_{(HC,\,PR)}$ can improve forecast skill for summer WNP precipitation.

The reorganized samples are further divided into six groups based on $r_{(HC,\,PR)}$ values. The PDFs of the forecast skill for summer WNP precipitation based on these groups of samples are shown in figure 5. As expected, the samples with larger $r_{(HC,\,PR)}$ values have higher forecast skill for summer WNP precipitation. Additionally, the kurtosis of the PDF increases with larger $r_{(HC,\,PR)}$, confirming that given the forecast members with larger $r_{(HC,\,PR)}$, the prediction performance for summer WNP precipitation is more convergent between these members. Figure 5 also shows that even in the group with the highest $r_{(HC,\,PR)}$ values (0.7–0.8, which means the IPWP Hadley circulation explains 49%–64% of the total variance of summer WNP precipitation), the most probable forecast skill for summer WNP precipitation remains below 0.6. This implies that $r_{(HC,\,PR)}$ is not the only factor affecting the forecast skill for summer WNP precipitation. It is worth pointing out that the forecast skill for summer WNP precipitation in GloSea5 increases with larger $r_{(HC,\,PR)}$ to some extent (figures 4(c) and 5).

4. Summary

Using 23 years of ensemble global seasonal hindcasts from the UK Met Office GloSea5, we evaluated forecast performance for summer WNP precipitation and the effect of the relationship between spring IPWP Hadley circulation and summer WNP precipitation. GloSea5 produces a stronger-than-expected relationship between spring IPWP Hadley circulation and summer WNP precipitation, and it has moderate forecast skill for summer WNP precipitation (with the most probable correlation coefficients around 0.55 in resampled forecast members). We randomly reorganized the 28 ensemble forecast members of GloSea5 5000 times, and concluded that those samples with larger $r_{(HC,\,PR)}$ have higher forecast skill for summer WNP precipitation than those with lower $r_{(HC,\,PR)}$. These results indicate that, on the one hand, $r_{(HC,\,PR)}$ plays an important role in the seasonal prediction of summer WNP precipitation in GloSea5; on the other hand, seasonal forecast performance for summer WNP precipitation in GloSea5 increases with larger $r_{(HC,\,PR)}$ (e.g. > 0.6) even when $r_{(HC,\,PR)}$ is much larger than the expected value ($r = 0.45$), which means that the skill of GloSea5 is overly reliant on $r_{(HC,\,PR)}$. To better predict summer WNP precipitation, ideally, GloSea5 needs to describe a more realistic $r_{(HC,\,PR)}$, and at the same time reproduce other factors whose teleconnections are responsible for predictability of summer WNP precipitation.

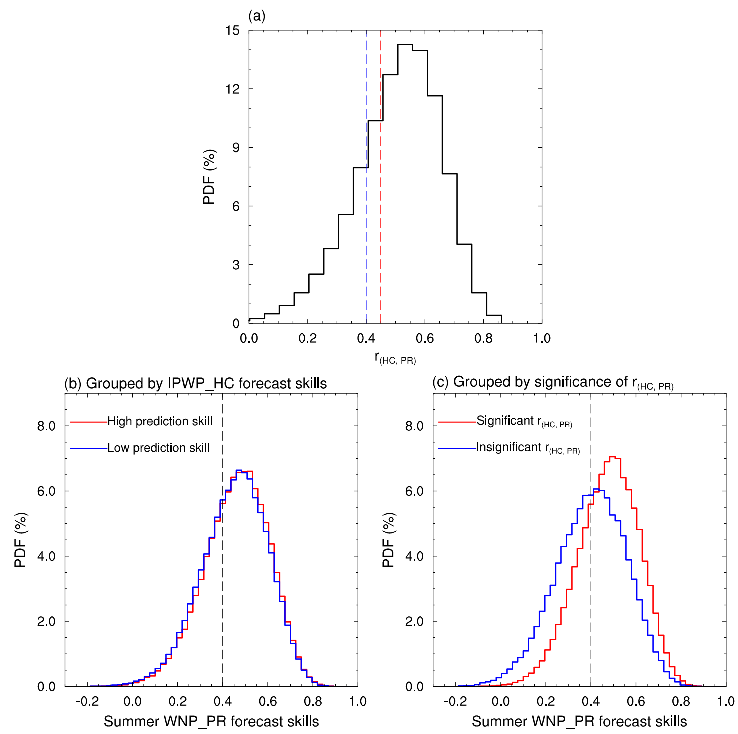

Figure 4. (a) PDF of $r_{(HC, PR)}$ based on the 28 × 5000 reorganized samples. The blue dashed line indicates the 95% confidence level. The red dashed line indicates the $r_{(HC, PR)}$ in observations. (b) PDF of the forecast skill for summer WNP precipitation based on the samples with prediction skill of IPWP Hadley circulation larger (red line) and smaller (blue line) than its mean value (0.78). The black dashed line indicates the 95% confidence level for the summer WNP precipitation forecast skill. (c) As in (b), but the PDFs are based on the samples with significant $r_{(HC, PR)}$ (red line) and insignificant $r_{(HC, PR)}$ (blue line).

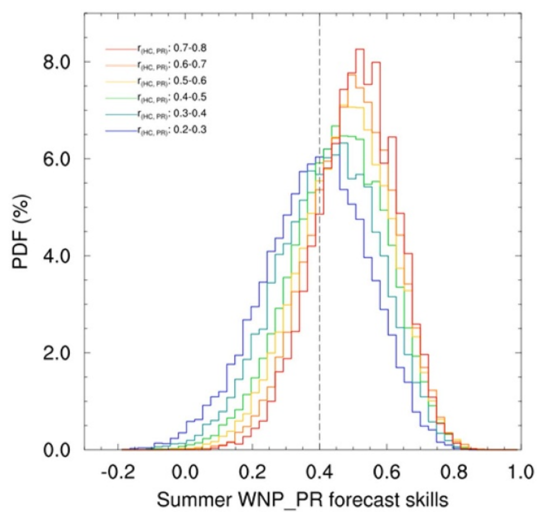

Figure 5. As in figure 4(c), but based on different $r_{(HC, PR)}$ values within 0.2–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, and 0.7–0.8.

Some studies have evaluated the skill for summer WNP climate in GloSea5 (Johnson *et al* 2017), as well as in other seasonal forecast models (e.g. Chan *et al* 1998, Chan *et al* 2001, Camargo and Barnston 2009, Kosaka *et al* 2013). The present study evaluated GloSea5's ability to capture a cross-seasonal relationship, i.e. $r_{(HC, PR)}$, which represents the air–sea coupling processes cross-seasonally connecting the spring IPWP Hadley circulation and summer WNP precipitation. If these processes are not properly captured by dynamical models, the summer climate forecast skill will be limited even if the models properly reproduce the spring external forcing. For instance, higher forecast skill for spring IPWP Hadley circulation does not necessarily result in higher forecast skill for summer WNP precipitation (figures 3(b) and (d)). However, the $r_{(HC, PR)}$ can robustly influence the forecast skill for summer WNP precipitation, because $r_{(HC, PR)}$ is established through the air–sea coupling processes that guarantee the cross-seasonal influence of the spring IPWP Hadley circulation on the summer WNP precipitation (e.g. Kosaka *et al* 2013, Guo and Tan 2018b). Additionally, $r_{(HC, PR)}$ also represents the variance of the summer WNP precipitation explained by spring IPWP Hadley circulation. Although GloSea5 predicts the spring IPWP Hadley circulation quite well (with most probable prediction skill near 0.78), it affects the forecast skill for summer WNP precipitation (figure 4(b)) only if the IPWP Hadley circulation explains larger fractions of the WNP precipitation total variance, i.e. with larger $r_{(HC, PR)}$ values (figures 4(c) and 5). Thus, the $r_{(HC, PR)}$ is a potential source of the cross-seasonal forecast skill in seasonal forecast models like GloSea5. It is worth pointing out that another important factor affecting the seasonal forecast is the Madden–Julian Oscillation (MJO). Roxy *et al* (2019) suggested that the warming and expansion of the IPWP exert strong influence on the MJO cycle and subsequent precipitation over the WNP. Because the MJO plays an important role in affecting the subseasonal to seasonal prediction of the weather and climate over the IPWP, it is worth investigating how well GloaSea5 captures MJO dynamics, especially under the influence of the IPWP rapid warming background. The study of the MJO in GloSea5 is being continued, and the results will be reported in the future.

The limitation of this study is that $r_{(\mathrm{HC,\,PR})}$ does not reveal the detailed air–sea coupling processes governing the summer precipitation prediction skill in models. In the future, we should focus on the physical mechanisms that link spring IPWP Hadley circulation and summer WNP precipitation in these seasonal forecast models.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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